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Dynamometer Simulation of Truck and Bus Road Horsepower for Transient Emissions Evaluations

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DYNAMOMETER SIMULATION OF TRUCK AND BUS ROAD HORSEPOWER FOR TRANSIENT EMISSIONS EVALUATIONS

by

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The relationship between engine power and speed associated with vehicle operation on a roadway (speed-power relationship) was developed for two truck tractor-trailers and one city bus. Results of these determinations, along with data reported in the literature, were used to determine the power to be absorbed by a chassis dynamometer to simulate on-road driving of trucks and buses. The chassis dynamometer simulations are being used in tests to characterize emissions from heavy-duty vehicles

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Dynamometer Simulation of Truck and Bus Road Horsepower for Transient Emissions Evaluations

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ABSTRACT

Appropriate chassis dynamometer simulation of road power for truck tractor-trailers and buses were required for emissions evaluations. To establish such simulations, the power required to operate vehicles over a roadway (speed-power relationship) was determined for two truck tractor-trailers and one city bus. Results of these determinations, along with data reported in the literature, were used to determine the power to be absorbed by a chassis dynamometer to simulate on-road driving of trucks and buses. The chassis dynamometer is being used in the subsequent phases of this study involving emissions evaluations of heavy-duty vehicles.

THE PURPOSE OF THIS PAPER is to describe the findings associated with road power determination and simulation for heavy-duty trucks and buses. Included is a general discussion of road power, along with the results of evaluations on the road and on the chassis dynamometer. The results have been used to define the appropriate amount of power to be absorbed by a chassis dynamometer to simulate on-road driving of trucks and buses. Appropriate road power simulation is important for meaningful emissions evaluations on a chassis dynamometer. Subsequent studies, associated with this program, involve emissions evaluations on a chassis dynamometer.

PROGRAM DESIGN

The objective of this study was to establish appropriate dynamometer simulation of road power for use in emissions evaluations of heavy-duty trucks and buses. The approach toward meeting this objective involved review of the relevant literature, evaluation of several vehicles on the road, and the simulation of the resultant speed-power relationships on the chassis dynamometer.

The primary method used in this study for determination of power requirements on the road was the "coastdown" method. This involved determination of the speed-time curve during coastdown of the vehicle and then using this relationship, along with the total inertia of the vehicle, to calculate the speed-power relationship. Special emphasis was applied to appropriate interpretation of the resulting values.

The vehicles tested on the road were then installed onto the heavy-duty chassis dynamometer to establish dynamometer simulation of the speed-power relationship. In addition, some effort was made to determine the relationship between tire rolling resistance on the road and on the dynamometer.

CONDUCT OF THE PROGRAM

This study involved a literature review and evaluations of three vehicles. The vehicles evaluated were a single-drive-axle tractor-trailer, a tandem-drive-axle tractor-trailer, and a city bus. Evaluations were conducted with these vehicles operating on the road and on a programmable heavy-duty chassis dynamometer. These evaluations primarily involved "coastdowns" of the vehicles.

Two of the vehicles were tested under as near ideal conditions as practically attainable. Analysis of road power data obtained under ideal conditions (i.e., zero road grade, zero wind, standard temperature, standard road surface, etc.) were found to be straightforward and relatively simple. With one of these vehicles, good data illustrating the effects of sidewinds were also obtained.

The waterbrake power absorption units on the tandem-axle Clayton heavy-duty chassis dynamometer were replaced with eddy current power absorbers. Electronic programming of the system enables obtaining essentially any speed-power curve. By utilizing an electrical signal from the vehicle braking system, electrical braking of the dynamometer rolls is also provided. Each of the absorption units in tandem have dual rolls that are eight and five-eighths inches in diameter. Inertia simulation is provided by an appropriate combination of direct connected inertia wheels. The inertia wheels and eddy current power absorbers are shown in Figure 1. Maximum inertia simulations readily attainable are 49,000 pounds for single-drive-axle vehicles and 76,000 pounds for tandem-drive-axle vehicles.

DISCUSSION OF ROAD POWER

Proper understanding of the data generated in this study, or in other related studies, requires some general understanding of road power, and of the factors associated with its determination. This section provides a brief overview of the subject, and is intended as a ready source for a general understanding of road power determination and simulation.

The forces or resistance involved in operation of a vehicle on the road are as follows:

Total Resistance* = T + R + A + I + G

Where:
- T - Transmission and Driveline Losses
- R - Rolling Resistance of the Tires
- A - Air Resistance
- I - Inertia (affects accels and decels)
- G - Road Grade

*Engine friction can have some effect--see text.

ENGINE FRICTION - In coastdown testing, the transmission is placed in neutral and engine friction is not a factor. In all other operation of the truck, the engine friction is a factor if the engine speed on the dynamometer differs from that on road. Since slippage and the effective rolling radius of the tires, on the dynamometer and on the road, do differ (by an apparent two to three percent), this is a factor. In dynamometer operation, relative to operation on the road, one can run at the same engine speed or at the same vehicle speed, but not both. This is a relatively minor factor relative to total road power requirements, but does become significant relative to some component parts of the total road power.

TRANSMISSION LOSSES - The engine speed to vehicle speed relationships, as discussed in the previous section, apply to the transmission, but the affects are of much less significance. No significant difficulties are foreseen relative to transmission and driveline losses. When attempting to actually measure these losses, however, there are difficulties in actually simulating the same conditions that exist in actual operation on the road.

ROLLING RESISTANCE - The losses due to tire rolling resistance are a major contribution to total road power requirements. Difficulties relative to tire rolling resistance are that tire rolling resistance on the dynamometer apparently differs from that on the road, and that agreement has not been reached on the relationship between rolling resistance and vehicle speed. Reported relationships between total rolling resistance (i.e., tire plus drive train losses) and vehicle speed are expressed in the equations given in Table 1.

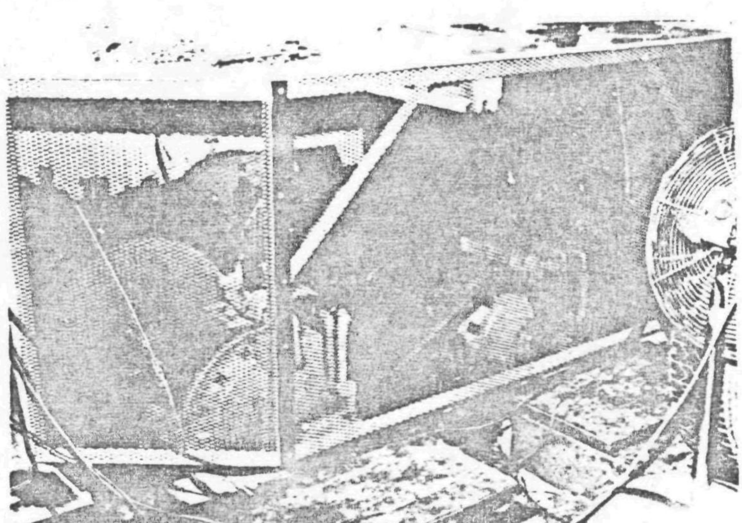

Figure 1 - Chassis dynamometer inertia wheels and eddy current power absorption units

Table 1 - Equations for Determination of Rolling Resistance

Equation No.	Equation in form of $F_1(C_1 + F_2V)W/C_2$	Reference
(1)	R = F(10 + 0.000V)W/1000[a]	1
(2)	R = 0.70(10 + 0.047V)W/1000[b]	1
(3)	R = F(10 + 0.050V)W/1000[b,c]	2
(4)	R = F(10 + 0.100V)W/1000[c]	3
(5)	R = 0.66(10 + 0.117V)W/1000	4
(6)	R = 0.60(10 + 0.117V)W/1000	1
(7)	R = 0.76(10 + 0.118V)W/1000	5

Where: R = Rolling drag in pounds
W = Vehicle weight
V = Vehicle velocity in mph
C = Some constant
F = Some factor

[a] Based on data from several tire manufacturers
[b] Derived from data given in a Figure
[c] Linear approximation

The effects of vehicle speed on rolling resistance, as given by these equations, is illustrated in Figure 2. As shown, the reported effects of vehicle speed on rolling resistance are not very consistent.

Rolling resistance is affected by tire type, temperature and pressure, and by the condition of the road. Specific, definitive references have not yet been found for the effects of these parameters on trucks. For cars there are considerable data available concerning the effects of type of tire. It is not known, however, how these data relate to truck tires.

It appears that the range of differences between available tires for trucks is similar to that for cars. With cars, the rolling resistance is reported to decrease by about 0.5 percent for each 1°F increase in ambient temperature.(6)* Experiments from this study, along with data given in the references, indicate that the preconditioning operation of the tires may be an even more important factor than ambient temperature. With the equivalent of about half vehicle payload on a truck tire, stabilized tire temperature increased by about 5°F for each 10 mph increase in vehicle speed.(1)

Wet roads are known to increase rolling resistance, probably due to the cooling effect. (3) A probable, but currently undefined, factor is the effect of sunshine on the temperature of the road surface and the air immediately above the surface of the road.

AIR RESISTANCE - Air resistance and rolling resistance are the two primary contributors to total road power (when operating on level road). Air resistance is significantly affected by a number of factors (i.e., vehicle shape, gap between tractor and trailer, air deflectors, wind speed, wind direction, air turbulence, air density, and possibly others). Wind speed and direction are especially troublesome, since they have a large effect, they are not controllable, and there are apparently no fully satisfactory correction factors available. Also, even if one finds sufficient "no-wind" days in which to conduct the road testing, the resulting values will not be representative of normal operation. The normal situation is for there to be wind.(4,7)

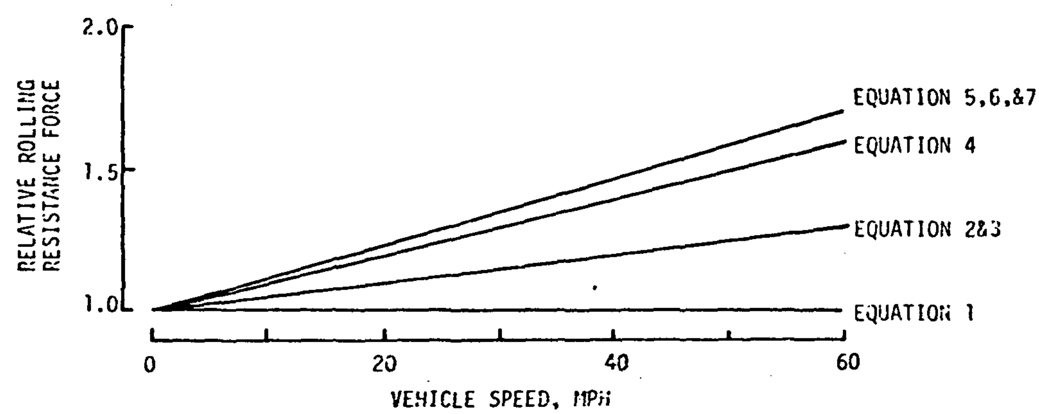

Figure 2 - Rolling resistance vs vehicle speed

*Numbers in parentheses designate references at end of paper

Vehicle Shape - One cab-over-engine (COE) configuration had 13 percent more air resistance than a simplified conventional cab. Other COE configurations had 2 to 14 percent more air resistance than a simplified conventional cab. (8) Definitive data, however, does not appear to be available in the literature.

Gap Between Tractor and Trailer - The effect of gap between the tractor and the trailer is significant. This effect on air resistance appears to be equal to or greater than a 0.4 percent increase in air resistance per 1 inch increase in gap. (2,8)

Air Deflectors - At zero yaw angle (yaw angle is a measure of sidewind), a "standard" type air deflector is reported to reduce the air resistance by a little over fifteen percent. As the yaw angle (sidewind) increased, the air deflector was less effective. The overall average for all tests conducted was a five percent reduction in air resistance. (4) In an evaluation with the tractor-trailer road tested in this project, cursory analysis indicated a reduction in air resistance of about ten percent under conditions that approached the national average wind speed and direction relative to the road.

Wind Speed and Direction - A more correct term would be wind speeds and directions. In real life, wind speed and direction is seldom constant; this is especially true at very low wind speeds. Almost instantaneous variations of plus or minus 100 percent in wind speed and 180 degrees in wind direction were found to be fairly common.

Wind parallel to the direction of vehicle travel affects the total air velocity relative to the vehicle. It appears that this effect can be represented as follows:

$$\text{Air Res.} = \text{Air Res. at 0 Wind} \times [(V \pm /\!/W)/V]^2$$

Where: V = Vehicle velocity
//W = Wind speed parallel to road

This effect does not completely cancel out by operation in both directions over the road. With a vehicle speed of fifty mph and a wind of five mph parallel to the road, the resulting increase in air resistance (relative to a test in both directions with zero wind) is about one percent. The effect at other wind speeds is a function of the square of the wind speed (e.g., four percent increase with a parallel wind of 10 mph, nine percent with 15 mph, sixteen percent with 20 mph wind).

A major difficulty associated with wind however, is the apparent large effect of side winds. (4,8) Side winds are generally defined in terms of yaw angle; yaw angle is the direction of the effective air speed relative to direction of vehicle travel. Yaw angle can be determined as follows:

$$\text{Yaw Angle} = \text{Arctan} [\perp W/(V \pm /\!/W)]$$

Where: ⊥W = Wind component perpendicular to road
//W = Wind component parallel to road

Based on available data for tractor-trailers, the air resistance increases about 3.5 percent (an apparent low of around 1.5 percent and a high or around 6 or 7 percent) per degree increase in yaw angle above a couple of degrees of yaw angle. (4,8) At a vehicle speed of 50 mph, the yaw angle increases by approximately one degree per each mph increase in the wind speed component perpendicular to the road. As an example, a 5 mph side wind appears to increase the air resistance by about eighteen percent at a tractor-trailer speed of 50 mph.

Using the overall nationwide average wind speed of 9.5 mph, and assuming equal directional distribution relative to direction of vehicle travel, the overall average yaw angle comes out to be about seven degrees at a vehicle speed of 50 mph. With tractor-trailers, the overall effect of the nationwide average wind speed would be about a fifteen percent increase in the total power required at a vehicle speed of 50 mph.

Since accepted correction factors for yaw angle are not available, mathematical analyses of road data requires negligible yaw angles during the collection of the data (negligible might be defined as less than a half mph side wind).

Air Turbulence - Air turbulence can also increase the air resistance of a vehicle. Determination of the effect of the atmospheric turbulence on the vehicle, however, is extremely difficult. The only presently available method to account for air turbulence is to conduct the road evaluations when it is nonexistent or negligible. In general, turbulence tends to decrease with decrease in wind speed. Turbulence, however, is a function of more than wind speed.

Air Density - The air density is a function of the temperature, pressure, and humidity. Air resistance of a vehicle increases as a direct function of increases in air density. Air resistance data can be corrected to standard conditions (light-duty applications utilize 68°F and 29.0 in. Hg) as follows: (6)

$$\text{Correction to Std. Cond.} = (460 + T)/528 \times 29.0/\text{Baro.}$$

Where: T = Air Temperature, °F
Baro = Barometirc Pressure, inches Hg

If the air resistance component of the vehicle can be determined from the road-test data, correction to standard conditions is straightforward. Fortunately, around San Antonio, conditions of minimum wind are generally associated with atmospheric parameters that result in a correction of less than one percent.

INERTIA - Inertia is important in accelerations and decelerations (it does not affect steady-state operation). The total inertia (expressed in units of weight) of a vehicle is equal to the weight of the vehicle plus the equivalent weight of the rotating components (primarily the complete wheel assemblies). In operation on the road, all of the wheels on the vehicle are rotating. In operation on the dynamometer, not all wheels rotate. The inertia of a wheel assembly can be determined by laboratory evaluation(9) or can be determined from the available literature.(1,10) Some values given in the literature are as follows:

Tire Size	Inertia of Wheel Assy., lb-in-sec^2
11:00×24.5	177(1) (198)(10)
10:00×20	129(1)

The equivalent weight is equal to I/R^2, and the equivalent weights are reasonably similar for these two sizes of wheel assemblies. The values result in an equivalent weight of about 150 pounds per wheel assembly (value varies depending on actual rolling radius of the tire). Using this value, the total inertia of a 18-wheel tractor-trailer, with a weight of 54,000 pounds, would be as follows:

Total Equiv. Weight = 54,000 + 2700 + Other Inertia

Where: 18×150 = 2700
Other Inertia is considered negligible.

Of the 18 total wheels, eight rotate during operation on the dynamometer. The remaining ten need to be accounted for in comparisons between coastdowns on the road and on the dynamometer.

ROAD GRADE - Road grade is a very significant factor in road testing of vehicles. Road testing of vehicles (especially trucks) required long sections of highway having uniform grade: a maximum grade of 0.5 percent and constant within ± 0.1 percent.(1,6) The effect of 0.1 percent grade (5 feet per mile), however, is equivalent to a ten percent change in rolling resistance. Even this effect can be significant. Sections of such highway are reported to be rare(1); this holds true for the area around San Antonio. This can result in having to conduct the coastdowns in two or more parts, which can affect the analyses. If the road grade is small and constant, its effects are essentially neutralized by operation in both directions over the same section of the road.

METHODS FOR DETERMINING ROAD POWER - Application of a suitable torquemeter for heavy trucks, is reported to be very difficult, and no results have been published in which a torquemeter was used to determine aerodynamic drag.(10) Other methods, such as measurement of fuel flow, or other parameters related to engine power output, does not enable determination of the actual power required. When carefully conducted, however, such methods can be used to transfer operation on the road to dynamometer operation. Vehicle coastdowns appear to be a generally accepted method for determining the road power requirements of heavy-duty vehicles. Essentially all of the factors previously discussed equally affect coastdown and steady-state evaluations.

The application of the coastdown method is straightforward, provided you have a long section of level highway (zero grade) and ideal atmospheric conditions (primarily no wind). Obtaining all of these conditions simultaneously is reported to be extremely difficult.(1,4,7) This was also found to be true for the evaluations conducted in this study. Ironically, such ideal conditions produce results that are somewhat incongruous to actual vehicle operation.

In forty cities at seven o'clock in the morning, the average wind speed was about 7 mph(7). Daybreak is generally the calmest part of the daylight hours. Assuming a normal wind distrubtion, that seven minus zero mph is equal to three standard deviations, and no bias in wind direction relative to the road; the wind perpendicular to the road would be less than one-half mph about two percent of the time (i.e., about one day out of fifty would have ideal wind conditions). Experience around San Antonio in the spring make the two percent appear optimistic; ideal conditions for a long enough period to obtain data were essentially nonexistent. In summer, however, such periods of "no wind" occurred a little more often than two percent of the time.

One approach toward defining road power is to measure all of the individual components, except for air drag, and to conduct coastdown tests to determine the total power required. The air drag is then determined by subtracting the power required by the components from the total. The expected results are illustrated by data given in Reference 1. In that reference, data was obtained on a vehicle at several different vehicle weights. One would expect the air drag to remain nearly constant, or at least consistent (i.e., configuration having highest air drag at high speed to have highest air drag at slower speeds). The actual results, however, were a plus or minus seven percent variation in air drag at 60 mph and a plus or minus sixteen percent variation at 30 mph.

ROAD POWER EVALUATIONS

Road power evaluations were conducted with two truck tractor-trailers and one city bus. The more extensive and better data were generated with the second truck tractor-trailer and the bus.

TANDEM-AXLE TRUCK TRACTOR - Initial road-load data were obtained using an IHC truck-tractor with a 44 foot long, tandem-axle, enclosed trailer. This unit is shown in Figure 3 and described in Appendix A. The trailer was loaded, as required, with concrete blocks to simulate an empty trailer, half payload (70 percent of the rated GCW), and rated GCW. These initial road-load data were obtained under less than ideal conditions due to the inclement weather that occurred during the evaluations.

The evaluations on the road with this vehicle consisted of steady-state operation and coastdowns. On the basis of dynamometer settings required, the steady-state and the coastdown data generally agreed within seven percent or less. The results obtained, however, are higher than the reported or calculated results based on ideal wind and weather conditions. These data uncorrected for wind, along with data from two references, are given in Table 2.

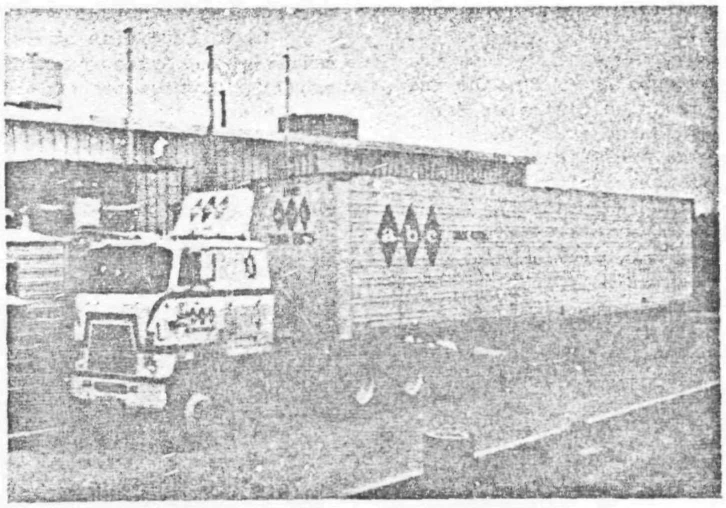

Figure 3 - Tandem-axle truck tractor with tandem-axle trailer

Table 2 - Road Horsepower of Tandem-Axle Truck Tractor

Speed, mph	Total Road Horsepower: Data From this Study[a] 34000[b]	54000	78000	Ref. 11 54000[c]	Ref. 2[d] 32000[d]	(54000)[e]	(54000)[f]
30	49	60	77	--	--	--	--
40	81	95	122	--	70	92	88
50	130	145	180	135	113	145	135

[a] Cab-over-engine tractor with wind deflector and tandem axle trailer
[b] Vehicle total weight in pounds
[c] Based on equations in the Recommended Procedure
[d] Thermostatically controlled radiator cooling shutters covered due to considerable effect on drag
[e] Data adjusted to 54,000 pound truck weight
[f] Estimate for with wind deflector

The data generated on this vehicle were with a wind speed of around ten miles per hour blowing at an angle of about 45 degrees relative to the road. Interpolation of the empty, half, and full load data, results in a horsepower value at half load between 145 and 150. This value is about 10 percent higher than the 135 horsepower values derived from References 2 and 11. This difference is likely due to the wind that occurred during these evaluations.

Based on the experience with this vehicle, it was primarily concluded that the following were either very desirable or necessary: a test road less than one hour driving time from the laboratory; more stable weather conditions, (i.e., summer); and provisions for conducting the evaluations at a time of essentially zero wind speed. All of these criteria, along with a number of other equipment and operating improvements, were incorporated prior to conducting the evaluations with the other two vehicles.

TEST ROAD AND CRITERIA - The initially selected road for vehicle testing was located about ninety miles south of the chassis dynamometer laboratory. This made it difficult to assure the atmospheric conditions in that area and resulted in a major effort even when testing had to be aborted because of unfavorable conditions. Therefore, a determined effort was again made to locate a suitable road for the vehicle testing. Airport runways and other non-road surfaces had already been excluded during the initial search as not being available or suitable.

A section of the access road to an interstate highway (Interstate 10) was subsequently selected. This section of road is located about thirty-five miles east of the laboratory, a distance just long enough to provide sufficient warm-up of the vehicle. The roadway was acceptably flat, the surface was in good condition, and there was essentially no traffic. The absence of traffic was because of the low population density in that area and the fact that this access road dead-ends about a mile from the section utilized. The average grade (or slope) of the 0.9 mile section used was 0.11 percent, and the maximum variation was plus or minus 0.11 percent (0.11 percent is equal to six feet per mile).

Since the mimimum wind speed generally occurs around daybreak, provisions were made to begin the actual testing at daybreak (safety, annoyance, and operating considerations precluded testing while it was still dark). Measurement of fuel flow at constant vehicle speeds, or of some parameter representative of fuel flow, is time consuming and does not enable calculation of the total road power requirement. (It can, however, provide useful data for setting a load into the chassis dynamometer). Therefore, with the very minimal amount of "no-wind" test time available, only coastdown evaluations were subsequently conducted with the two remaining vehicles.

A "fifth-wheel" was used to measure the speed of the vehicle. Three precautions were found to be essential in using a fifth-wheel: absolutely rigid mounting to the vehicle frame (vibration shows up as speed variation), elimination of electronic noise (without excessive damping of the response), and frequent calibration checks. Calibration of the velocity of travel was conducted using distance versus time measurements. Distance measurement was calibrated prior to this, with the "fifth-wheel" mounted on the vehicle, using a precisely measured distance on the road.

Wind speed and atmospheric temperature and humidity were measured at the test site. Barometric pressure was measured at the laboratory, after it was determined that this method provided the required accuracy. The rotating vane wind speed instrument used had a readability of one mile per hour and an accuracy of better than one mile per hour at low speeds. Temperature and humidity were determined using wet and dry bulb thermometers.

SINGLE-AXLE TRUCK TRACTOR - The single-axle truck tractor and single-axle trailer evaluated are shown in Figure 4 and described in Appendix B. The tractor was of conventional design and the tractor-trailer had a GCW of 42,000 pounds. The evaluations were conducted at tractor-trailer combined weights of approximately 25,000 and 41,200 pounds. These weights were selected on the basis of the maximum variation that could be obtained without repeated rearrangement of the inertia wheels on the chassis dynamometer. Based on an equivalent inertia of 165 pounds in each wheel assembly on the truck, the total equivalent inertias were 27,300 and 42,900 pounds.

At the lower vehicle loading, coastdowns were conducted from an initial speed above 60 mph to a final speed below 20 mph. At full-load, two coastdown segments were required, and speeds above 60 mph were not practical to obtain. Therefore, the combined coastdowns at full-load were from about 55 mph to below 15 mph. An attempt was made to obtain five coastdowns in each direction with each vehicle loading. The mimimum number was three coastdowns producing repeatable results.

It was determined that the available methods for processing the data, such as that given in Reference 9, did not account for side-winds or for variation in road grade (slope), and therefore, were not directly applicable. Therefore, a method was developed that involved calculation of the road power at each five mile per hour increment in vehicle speed; this enabled incorporating side-winds and road grade into the calculations. The method is summarized in Appendix D. Results of the data obtained, along with calculated horsepower values, are summarized in Tables 3 and 4.

To put these data into perspective, the following discussion is presented. About five percent difference in horsepower at 50 mph (e.g. 105 vs 100 hp) results from any of the following:

- 0.15% Road Grade
- 2 [illegible]h Side Wind
- [illegible] n Head Wind
- [illegible]mph Vehicle Speed

Therefore, a five percent difference in road horsepower at a vehicle speed of 50 mph is actually not very significant. With light-duty vehicles, the EPA generally accepts data which differs by less than seven percent (A/C No. 5[illegible]) (6) in the direction opposite to that produced by these previously listed factors.

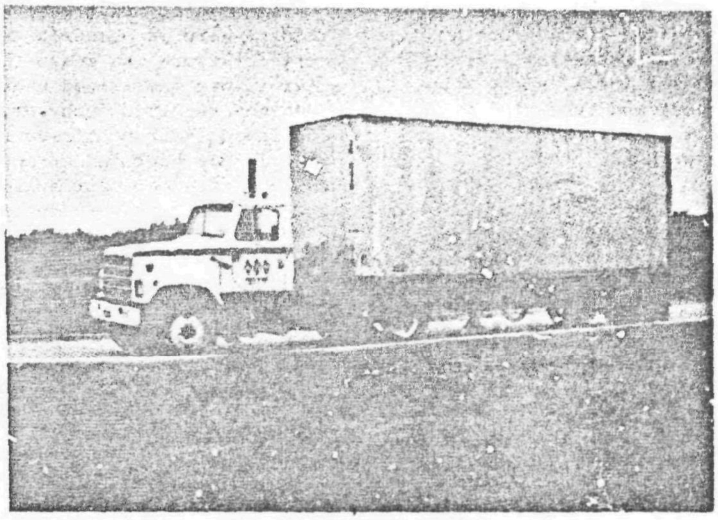

Figure 4 - Single-drive-axle truck tractor with single-axle trailer

Table 3 - Road-Power Evaluations-TT Road 2

Vehicle Speed mph	Road Hp from Coastdowns			Calculated Hp Using Recommended Procedure[a]		
	41200	25600	Δ	41200	25600	Δ
50	127	105	22	120[a]	100[a]	20
45	103	80	23	96	79	17
40	83	60	23	76	61	15
35	65	47	18	60	46	14
30	48	35	14	46	34	12
25	34	26	8	34	25	10
20	25	18	7	25	17	8

[a]Values calculated at 50 mph using EPA Recommended Procedure and assuming constant rolling resistance:
Total Hp = 0.67×(Height - 0.75)×Width×(V/50^3 + 0.00125×Weight×(V/50)

Table 4 - Comparison of Road and Calculated Horsepower

Vehicle Speed mph	Road Hp/Calculated Hp		
	41200	25600	Avg.[a]
50	1.06	1.05	1.06
45	1.07	1.01	1.04
40	1.09	0.98	1.04
35	1.08	1.02	1.05
30	1.06	1.02	1.04
25	1.00	1.07	1.04
20	1.01	1.07	1.04
Avg.	1.05	1.03	1.04

[a]Provided as a matter of potential interest

The data in Table 3 indicate that for the tractor-trailer tested, the EPA Recommended Practice(11) provides a good estimation of the road horsepower required at a vehicle speed of 50 mph. Also, these data at speeds other than 50 mph agree reasonably well with values calculated using the equation derived from the EPA Recommended Procedure, along with the assumption that the rolling resistance remains constant with speed. The EPA Recommended Procedure only provides an equation for 50 mph; it does not define power requirements at other vehicle speeds.

With this vehicle, opportunities occurred that enabled obtaining data at two different conditions of almost direct side-winds. These data are summarized in Table 5. At a vehicle speed of 50 mph the coefficient of air resistance (when all of the effect of the side-wind is applied toward the air resistance) increased about three percent per degree increase in yaw angle. This value agrees with the increase of three and one-half percent previously estimated on the basis of the data provided in the literature.

Table 5 - Effect of Side Winds on Road Power

Vehicle Speed mph	At a Vehicle Weight of 25600: Road Hp at 0 Wind	Road Hp as % of the Hp at 0 Wind: 3.5 Wind[a]	12.5 Wind[a]
50	105	109%	129%
40	60	109%	133%
30	35	108%	128%
20	16	110%	129%
	Avg.	109%	130%
	ΔHp/mph Wind	2.6%	2.4%

[a] Approximate side wind in mph

Following the evaluations on the road, the truck-tractor was evaluated on the chassis dynamometer as shown in Figure 5. A view of the fans for cooling of the tires on the drive wheels is shown in Figure 6. Also shown in Figure 6 is the weight added to increase traction of the tires and the "fifth-wheel" assembly.

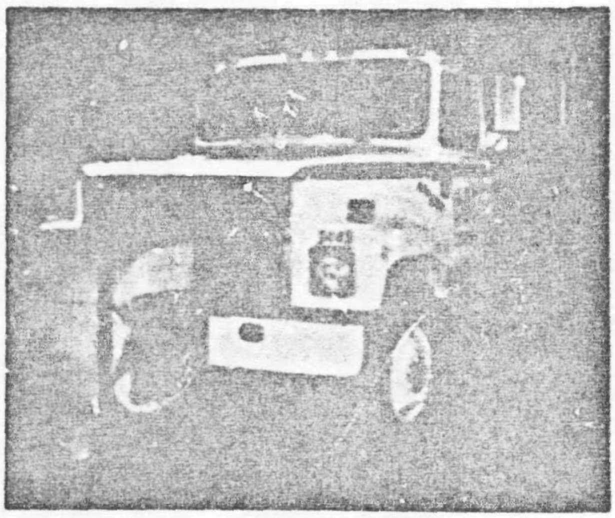

Figure 5 - Single-drive-axle truck tractor on the chassis dynamometer

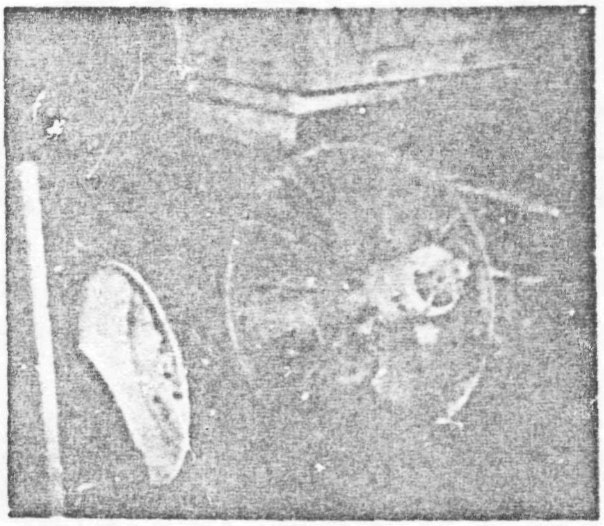

Figure 6 - Fan for cooling of the drive wheels

Coastdowns were conducted with the truck mounted on the dynamometer and with the dynamometer system itself to determine system power absorption. These coastdowns were conducted with no-load in the dynamometer and with a constant dynamometer load setting that was reasonably representative of the horsepower required on the road. By carefully maintaining consistent preconditioning (thirty minutes at 40 mph, or the equivalent) before each series of coastdowns, repeatable results were obtained. The results of the coastdown evaluations on the dynamometer are summarized in Tables 6 and 7. These data indicate that some, but relatively minor, differences in net horsepower result from changes in the amount of horsepower absorbed by the eddy-current dynamometer.

On the chassis dynamometer, the "rolling resistance" does not appear to be linear; it appears to increase as the velocity increases. (It appears, but these data do not prove, that rolling resistance is essentially constant on the road and is a function of velocity on the dynamometer. If this is true, it would explain the reason for the greatly conflicting equations for expression of rolling resistance that were found in the literature and previously discussed in this paper.

The data in Table 8 show that, after performing the necessary mathematics and programming the dynamometer, good simulation of the road results can be fairly readily obtained. This demonstrates that, if the road horsepower curve is known, the dynamometer being used can be programmed to closely simulate that horsepower curve.

It appears that the method in the EPA Recommended Procedure(11) to account for the rolling resistance may not be applicable to this tractor-

Table 6 - Dynamometer Coastdown Evaluations
26200 Inertia

Dyna. Speed, mph	Net Hp Calc. from the Coastdowns with 26200 Inertia			
	50 Load (T)[a]	0 Load (T)[a]	50-0[a]	Dynamometer (D)[b]
60	56.5	53.1	3.4	11.5
50	42.6	39.6	3.0	8.0
40	30.9	28.7	2.2	5.6
30	21.0	19.8	1.2	3.4
20	12.7	12.2	0.5	1.8
10	5.7	5.7	0.0	0.7

[a] Values obtained with the truck on the dynamometer
[b] Values obtained without a vehicle on the dynamometer; differences at 0 and 50 load settings were essentially negligible

Table 7 - Power Absorbed by Truck Tractor Tires and Drive-Train

Dyna. Speed, mph	Net Calc. Hp (T) - (D)[a]		Relative Hp with 50 mph = 1			
			(T) - (D)[a]		Calculated	
	50 Load	0 Load	50 Load	0 Load	(6.4 + 0.074 V)	Linear
60	45.0	41.6	1.30	1.32	1.29	1.20
50	34.6	31.6	1.00	1.00	1.00	1.00
40	25.3	23.1	0.73	0.73	0.74	0.80
30	17.6	16.4	0.51	0.52	0.51	0.60
20	10.9	10.4	0.32	0.33	0.31	0.40
10	5.0	5.0	0.14	0.16	0.14	0.20

[a] (T) is with truck on the dynamometer
[b] (D) is without a vehicle on the dynamometer

Table 8 - Comparison of Road and Dynamometer Coastdown Times

Dyna. Speed, mph	Road Hp	Dynamometer Hp			Coastdown Time, Sec.	
		R.R. + Fric.[a]	Absorbed Hp	Total	Road	Dyna.
50	97.2	44.5	53.2	97.7	0	0
40	58.1	31.0	26.5	57.5	19.4	19.5
30	35.8	20.7	14.8	35.5	43.7	43.8
20	18.8	12.5	6.2	18.7	73.9	73.5

[a] Calculated using extrapolation of the data obtained at 0 and 50 dynamometer load settings.

trailer on this dynamometer. The dynamometer horsepower settings at 50 mph for half-load are 57 based on coastdown evaluations and 71 based on the value calculated using the EPA Recommended Procedure.

Therefore, it was decided that data from coastdowns on the dynamometer be determined and used with each vehicle evaluated. However, data required to use the method given in the EPA Recommended Procedure will be obtained and recorded to enable subsequent comparisons of the methods in a planned future paper.

CITY BUS - Road horsepower evaluations were conducted on a bus obtained from VIA Metropolitan Transit in San Antonio. This bus is shown in Figure 7 and is described in Appendix C. In the road horsepower evaluations with this bus, good data were obtained at two load conditions under essentially no-wind conditions. The results of the road-power evaluations with the bus are summarized in Table 9. These data indicate that the EPA Recommended Procedure for trucks somewhat overstates the horsepower required with a bus. It appears reasonable to assume that these differences are due to the difference in air resistance between a truck and a bus and that the rolling resistance per unit of weight is about the same for a truck and a bus. Using such assumptions produces results given in Table 10.

These data indicate that the force required to overcome rolling resistance can be assumed to be essentially constant and that the air resistance force with a bus is lower per unit of frontal area than with a truck. The air resistance force per unit of frontal area with a bus appears to be about 0.85 as great as that for a truck. This seems reasonable since the bus is significantly more streamlined than a truck. Reference 3 reported an air resistance coefficient of 0.6 to 0.7 for a bus, and 0.8 to 1.0 for a truck.

DYNAMOMETER SIMULATION

Using a programmable dynamometer, the procedure developed for road load simulation of a vehicle on the dynamometer involves establishing the speed-power curve, determination of inertia simulation, and determination of system friction.

SPEED-POWER CURVE - The equation selected for calculation of the speed-power curve to be used for evaluations on the chassis dynamometer is as follows:

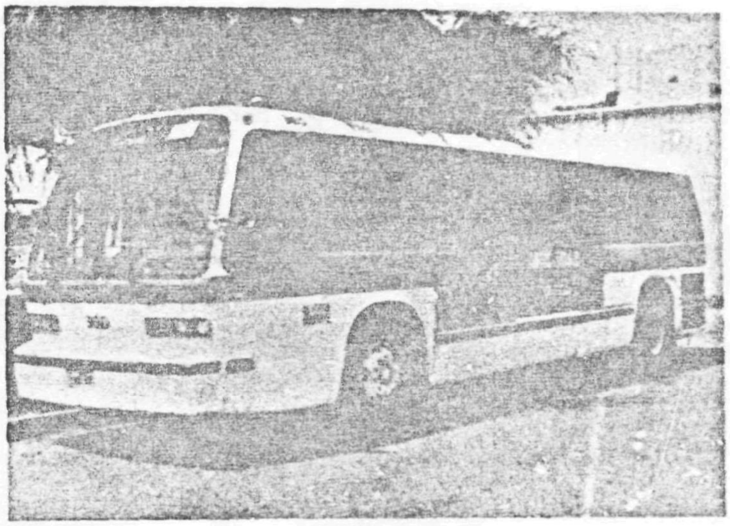

Figure 7 - City Bus

Table 9 - Road-Power Evaluations - Bus Road 3

Vehicle Speed, mph	Road Hp from Coastdowns[a]			Rec. Proc. for Trucks		
	31700	25700	Δ	31700	25700	Δ
50	84.0	73.9	10.1	88.5	81.0	7.5
45	67.1	59.0	7.9	--	--	--
40	53.2	46.6	6.6	--	--	--
35	41.8	36.3	5.5	--	--	--
30	32.6	27.8	4.8	--	--	--
25	25.1	20.9	4.2	--	--	--
20	19.1	15.3	3.8	--	--	--

[a]Based on best curve fit through the individual data at the various speeds.

Table 10 - Air and Rolling Resistance of a Bus

Vehicle Speed, mph	Air Resis. Hp[a]	Rolling Resistance Hp at 31700 lbs ΔRR by Difference[b]	Rolling Resistance Hp at 31700 lbs Calc. by EPA Proc.[c]	(ΔRR - EPA) ÷ Total Hp×100[d]	(ΔRR - EPA) ÷ 84.0×100[e]
50	41.4	42.6	40.8	2.1	2.1
45	30.2	36.9	36.7	0.3	0.2
40	21.2	32.0	32.6	-1.1	-0.7
35	14.2	27.6	28.5	-2.1	-1.1
30	8.9	23.7	24.4	-2.1	-0.8
25	5.2	19.9	20.4	-2.0	-0.6
20	2.6	16.5	16.3	1.0	+0.2

Vehicle Speed, mph	Air Resis. Hp[a]	Rolling Resistance Hp at 31700 lbs RR by Difference[a]	Rolling Resistance Hp at 31700 lbs Calc. by EPA Proc.[c]	(ΔRR - EPA) ÷ Total Hp×100%	(ΔRR - EPA) ÷ 73.9×100%
50	41.4	32.5	33.3	-1.0	-1.1
45	30.2	28.8	29.9	-1.4	-1.1
40	21.2	25.4	26.6	-2.6	-1.6
35	14.2	22.1	23.3	-3.3	-1.6
30	8.9	18.9	20.0	-4.0	-1.5
25	5.2	15.7	16.6	-4.3	-1.2
20	2.6	12.7	13.3	-3.9	-0.8

[a]Average of the total minus the calculated rolling resistance horsepower values for the two loads evaluated and value adjusted for best fit to a cubic equation.
[b]Total horsepower minus air resistance horsepower.
[c]Calculated at 50 mph using EPA Recommended Procedure and assuming constant rolling resistance force.
[d]Difference in (road) and calculated rolling resistance horsepower divided by the total horsepower at the respective vehicle speed.
[e]Difference in the rolling resistance values divided by the total horsepower at 50 mph.

$$RLP = F\times0.67(H-0.75)W\times(V/50)^3 + 0.00125\times LVW\times V/50$$

Where:
RLP = Road Load Power in horsepower
F = 1.00 for tractor-trailer and 0.85 for city bus
H = Average maximum height in feet
W = Average maximum width in feet
LVW = Loaded vehicle weight in pounds

On the clayton dynamometer with eight and five-eights inch diameter rolls, the equation for determination of dynamometer torque and load are as follows:

Dynamometer Torque = Hp×134.8/mph, foot-pounds
Dynamometer Load = Torque×12/(Load Arm in inches), pounds

INERTIA SIMULATION - In keeping with the general provision in the EPA Recommended Procedure,(11) the equivalent inertia to set in the dynamometer system for evaluation of a tractor-trailer is to be equal to 70 percent of the gross combined weight. For buses the equivalent inertia is to be equal to the sum of the empty weight, half passenger load plus the driver (at 150 pounds per person), and the equivalent inertia weight of the nonrotating vehicle wheel assemblies. A deviation equal to one percent of the total inertia, rather than the 250 pounds specified in the EPA Recommended Procedure, will be allowed.

For actual inertia simulation on the chassis dynamometer, the inertia of the wheel assemblies on the vehicle have to be accounted for. The resultant dynamometer inertia is as follows:

Total Inertia = EID + EIW
Where:
EID = Equivalent inertia of dynamometer system, pounds
EIW = Equivalent inertia of rotating wheels

This total inertia is to be used in the determination of system friction.

SYSTEM FRICTION - With the vehicle installed onto the dynamometer and with the appropriate inertia wheels connected, the total system absorbed horsepower will be determined using coastdowns. This can be accomplished by obtaining repeatable 60 to 5 mph coastdown speed vs time data and then solving for the instantaneous decelerations. From the instantaneous decelerations, the power absorption of the vehicle-dynamometer system can be determined as a function of vehicle speed. The speed-power curve for programming into the dynamometer controller can then be determined by difference between the total power required on the road and the power absorbed by the vehicle-dynamometer system.

The method is briefly described as follows:

(1) Obtain 60 to 5 mph coastdown data

(2) Obtain acceleration using the following equation:

dV/dt = Acceleration $= -(a_o + a_1V + a_2V^2)$

Where: a_o and a_1V represent rolling resistance

a_2V^2 represents air resistance

V = velocity of vehicle

Note: An acceptable alternate method is to graphically determine and calculate the acceleration at each five mph increment in vehicle speed.

(3) Calculate the power absorbed using the acceleration values, $F = ma$, and $Hp = F \times mph/375$.

(4) Develop the speed-power curve for programming the dynamometer by subtracting the power absorbed by the vehicle-dynamometer system from the total power required on the road.

(5) Calculate the speed-load curve to program into the dynamometer.

SUMMARY AND CONCLUSIONS

An improved road-load simulation method has been developed for use in operating large trucks on a chassis dynamometer. The purpose of these improvements is to permit more realistic laboratory simulation of the way Class VII and VIII diesel tractors and city buses perform on the road. These improved procedures will be used in a laboratory investigation of regulated and unregulated emissions from large diesel trucks and buses operated over a transient driving cycle.

Analytical and experimental studies were performed to determine mathematically, under essentially ideal environmental conditions, the truck or bus power-speed characteristics. A city bus, a single-drive-axle tractor-trailer (Class VII truck), and a tandem-drive-axle tractor-trailer (Class VIII truck) were operated on-the-road under as near-ideal environmental conditions as possible. The "coastdown" method (time to decelerate from one speed to a lower speed) was used to compute road horsepower. With the tractor-trailer trucks evaluated, the power required on-the-road at fifty miles per hour generally agreed with values obtained using the appropriate portion of the equation given in the EPA Recommended Procedure for heavy-duty vehicle testing on a chassis dynamometer. The equation given in the EPA Recommended Procedure does not define the power requirements at other vehicle speeds.

From the road evaluations, a generalized expression for determining road horsepower at various vehicle speeds was developed. By use of the proper vehicle weight, frontal area and coefficients, a road-load can be computed. Next, the test vehicle is operated on the chassis dynamometer to determine the power absorbed by the drive train, the tires, the dynamometer bearings and by tire and inertia system windage. This is accomplished by running repetitive coastdowns. This absorbed power is then subtracted from the total power required on-the-road, to determine the power values for programming into the controllable power absorption unit on the chassis dynamometer.

A major finding of the study was the significant effect that non-ideal environmental conditions have on road-power. Side winds are especially significant, and merely operating both ways over a level course does not cancel out the effect. Since ideal conditions are not the norm, it is concluded that road-power relationships currently used are conservative. From the limited data obtained with side winds present, it appears that the use of ideal conditions (i.e., no wind, etc.) results in horsepower values that are ten to fifteen percent lower for tractor-trailer trucks at half payload.

Developing a generally accepted solution to the question of the effects of non-ideal conditions associated with operation on-the-road was beyond the scope of this study. Therefore, the primary evaluations involved data obtained on-the-road under essentially ideal operating conditions. The data obtained on-the-road and the method developed for programming the speed-power relationship into a controllable chassis dynamometer will be used in subsequent emissions studies. Results of these emissions measurements will be the subject of a future technical paper.

ACKNOWLEDGEMENT

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APPENDIX A

DESCRIPTION OF TANDEM-AXLE TRACTOR-TRAILOR

Description:	1981 IHC Transtar II Truck Tractor with Cab Over Sleeper
Transmission:	Eight Forward Gears
Chassis:	Tandem Drive Axles
GCW:	78,000 pounds
Tires:	11R24.5X (measured 20.5 inch Rolling Radius at Half Load)
Trailer:	Utility Trailer VIN 7L8 1719 006 Semi 13.3 feet high by 8.1 feet wide by 44 feet long Horizontal Ribs on the Sides 12 inch Radius on Front Vertical Edges 60 inches Gap between Tractor and Trailer

APPENDIX B

DESCRIPTION OF SINGLE-AXLE TRACTOR-TRAILER

Description:	1981 IHC S2500 Truck Tractor with Conventional Cab
Transmission:	Fuller Road Ranger RT9509 - Nine Forward Gears
Chassis:	Single Drive Axle - 158 Wheel Base
GCW:	42,000 pounds (with single Axle Trailer)
Tires:	11R22.5 (measured 19.5 inch Rolling Radius at Half Load)
Trailer:	13.3 feet high by 8.0 feet wide by 26 feet long Flat Top-Smooth Sides (no ribs) 12 inch Radius on Front Vertical Edges 38 inches Gap between Tractor and Trailer

APPENDIX C

DESCRIPTION OF CITY BUS

Description:	1981 GMC RTS II Bus, Model T70204
Transmission:	Three Speed Automatic
Chassis:	Single Drive Axle - Dual Wheels on Rear
GVW:	36,000 pounds
Tires:	11.00-22 (measured 21.5 Rolling Radius at 28,000 VW) Goodyear City Cruiser on Front, Goodyear Super Hi-Miler on Rear

APPENDIX D

METHOD USED FOR EVALUATION OF ROAD COASTDOWN RESULTS

1. Starting at the highest vehicle speed to the nearest 5 mph, determine the time required to decelerate in 5 mph increments. This was done for each of the coastdown charts produced in both directions of travel.

2. Taking into account the wind speed and direction during each coastdown, determine and eliminate any outliers in the data.

3. Determine a mean value most representative of a no-wind condition and of some specific ambient temperature.[a] Then average the mean values for the opposing directions of travel.

4. Determine total horsepower at each 5 mph increment of vehicle speed using: $Hp = (F \times V)/375 = 1.215 \times 10^{-4} \times Inertia \times A \times V$, where $A = ((V + 5) - (V - 5))/\Delta t \begin{smallmatrix} V+5 \\ V-5 \end{smallmatrix}$

5. Calculate approximate air resistance horsepower at 50 mph using the formula given in the EPA Recommended Procedure and adjust to ambient conditions experienced during the coastdowns. Calculate approximate rolling resistance by difference. Assuming air resistance horsepower is a function of V^3 and rolling resistance as a function of V, calculate air and rolling resistance horswpower at the other vehicle speeds.

6. Determine horsepower corrections for air resistance corrected to 68°F and 29.0 inches Hg, rolling resistance corrected to 68°F, and road grade to zero net percent using:

   Air Hp T & B Corr. = $(((460 + T)/528 \times 29.0/Baro.) - 1) \times Air\ Hp$
   R.R. Hp Temp. Corr. $\approx 0.005 \times R.R. \times (T - 68)$
   Grade Hp = $26.7 \times 10^{-6} \times W \times V \times \%\ Grade$

   Where:
   T = Air Temperature in °F
   Baro. = Barometric Pressure in "Hg
   R.R. = Rolling Resistance
   W = Weight of the vehicle
   V = Vehicle velocity in mph
   % Grade = Net effective road grade

7. Add the horsepower corrections to the total horsepower values determined in Step 4. These values represent the driving horsepower required to operate the truck at the respective speeds under "standard" conditions of 68°F, 29.0 inches of mercury, "no-wind", and zero road grade.

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[a] For data with a side wind, a mean value most representative of some specific side wind was used.